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TECHNICAL NOTE

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THE DESIGN AND OPERATION OF A CONTINUOUS-FLOW ELECTRODELESS PLASMA ACCELERATOR

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THE DESIGN AND OPERATION OF A CONTINUOUS-FLOW ELECTRODELESS PLASMA ACCELERATOR

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SUMMARY

A continuous-flow induction plasma accelerator utilizing argon, or argon seeded with mercury vapor, has been built and operated. Comparison of this alternating-current system with a previous investigation of a direct-current (d-c) accelerator indicated that the induction system is more effective at pressures below 1 mm Hg. Vane-deflection measurements indicated that there was an effective pumping action on the neutral gas.

INTRODUCTION

A large number of laboratories throughout the country are engaged in studies directed toward the development of gas flow systems operating at extremely high velocities. Some of the proposed applications of such flow systems are laboratory simulation of reentry conditions, high-specific-impulse propulsion systems for spacecraft, and various applications in materials research and development.

Several methods have been investigated for producing a high-velocity gas flow. These methods include transient flows (shocks) driven by various mechanisms, as well as a variety of continuous-flow systems: arc- or flame-heated jets, electrostatic ion accelerators, and electromagnetically driven plasma flows. The experimental investigation described in this paper is part of an NASA effort in the area of plasma and ion acceleration and is directed specifically toward the study of continuous magnetohydrodynamic flows.

Apparently the earliest experimental investigations of continuously operating electrically driven flows for the purpose of developing a usable flow system were conducted at the University of Michigan. Results were obtained with crossed-field devices utilizing hot-cathode arcs (ref. 1) and glow discharges (ref. 2). Some recent experimental investigations at the NASA Langley Research Center are reported in references 3, 4, and 5.

Evidence of continuous plasma acceleration with a "traveling cusp" system at very low densities (mean free path larger than apparatus size) has been reported in reference 6. Such a system appears to be theoretically limited to low power inputs and, hence, to operation at quite low densities (see ref. 7).

The apparatus described herein is a completely electrodeless system; that is, both ionization and driving force are produced by induction. This device has been operated over a pressure range from 0.005 mm Hg (which represents the lower limit of the vacuum system) to 25 mm Hg (at which pressure the heating due to the high gas temperature becomes excessive). The apparatus has been operated at a power input of 20 kilowatts. This accelerator is believed to be unique in basic design as well as in its effective electrodeless operation over a broad pressure range. Without modification of the basic design, it is believed that the operation of this system may be extended to higher power levels, larger geometry, and a greater pressure range.

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APPARATUS AND PROCEDURE

Accelerator Apparatus

A schematic diagram of the physical arrangement of the accelerator apparatus is shown in figure 1 and a photograph, in figure 2. The flow system, exclusive of the accelerator section, was the same closed-circuit duct that was used for the experiments described in reference 4. The vacuum pump, operating at a capacity of only about 1 cubic foot per minute, was used together with a controlled leak in order to maintain a constant pressure of argon in the system. The motion of the gas in the system due to the pump and the leak only (before the accelerator was turned on) was so slight that it was not detectable with the measuring apparatus used. For experiments with pure argon, in which no mercury-vapor seeding was used, a second flow system was built which was similar in basic design to that shown in figure 1 except that all the ducting exclusive of that in the accelerator region was constructed of 75-millimeter-diameter glass pipe.

The ducting in the accelerator region consisted of a section of 75-millimeter-diameter Pyrex tubing joined to a section of 100-millimeter-diameter Pyrex tubing. A 10-kilocycle drive coil was mounted about the 75-millimeter tube at this juncture and a 30-megacycle ionization coil, about the 100-millimeter tube. The 30-megacycle radio-frequency oscillator had an output of 1,200 watts. The power delivered to the gas by this coil was somewhat less than 1,000 watts, as estimated from measurements similar to those described in reference 8. The 10-kilocycle motor generator had an output of 15 kilowatts continuously or 20 kilowatts for short periods, at a maximum voltage of 440 volts. An iron wire core contained in a 50-millimeter-diameter Pyrex tube was mounted coaxially through both coils, the wire extending some 25 centimeters into the 100-millimeter tube.

Measurement Apparatus

Measurements of the gas velocity were made by means of the vane (or pendulum) deflection method described in reference 2 and used also in the investigation reported in reference 4. The vane was located in the 100-millimeter tube approximately 10 centimeters from the radio-frequency (RF) coil. It consisted of a dielectric plate having a face area of 1 square centimeter, a thickness somewhat greater than 3 millimeters, and a weight of 0.98 gram.

An auxiliary vane was situated upstream of the accelerator section. This vane was much lighter than the downstream vane and had a larger area. Its deflection was therefore quite sensitive to the motion of gas through the duct. No velocity measurements were made with this vane, but it was used merely to monitor the flow direction and to detect the presence of any undesired gas flow that might occur, such as that resulting from a leak in the vacuum system.

Some measurements were also made with a pair of type 931 photocells displaced longitudinally downstream of the RF coil. This method of measurement is basically the same technique that is described in reference 9. Through collimated slits the photocells observe the changes in light intensity that occur 20,000 times per second (once each half-cycle). The photocells were connected to the inputs of a Tektronix Type 551 Dual-Beam Oscilloscope. Since the photocell nearer the coils observes a change in light intensity before the second photocell, the respective oscilloscope traces are displaced. This displacement, which actually represents a time lapse, can then be used together with the known photocell spacing to compute the longitudinal velocity of the light intensity changes.

For pressure measurements, mercury manometer tilt gages were employed. An orifice for pressure measurement was located in the wall of the 100-millimeter tube at the same longitudinal position as the vane.

Description of Accelerator Operation

The operation of the accelerator may be described briefly as follows: The system is pumped down to about 0.005 mm Hg. Then argon is bled into the system until the desired operating pressure is reached. The radio-frequency coil is next energized sufficiently to induce a discharge within the gas contained in the accelerator chamber. After this discharge is obtained, the drive coil is then energized, the magnetic field of which induces the large currents in the plasma required for its acceleration. The addition of the 10-kilocycle power results in both an increase in the intensity of the light emitted from the plasma and a change in its shape from a ring to a form which extends down the tube for 10 to 30 centimeters. That this action is accompanied by acceleration of the gas is demonstrated by observation of the deflections of the vanes. Both upstream and downstream vanes swing in the same direction (fig. 3), an effect which indicates that the gas is being pumped around the duct. Velocity measurements may be made by comparing photographs of the vanes in both the deflected and the undeflected positions.

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RESULTS AND DISCUSSION

Velocity Measurements

The vane deflections used to obtain the plasma velocity estimates represent the combined effect of both neutral particles and charged particles. Several sources of error are inherent in this type of measurement, as discussed in reference 2; but when the vane-deflection velocity formula is applied at relatively low velocities and with conservative estimates of the gas parameters, this formula should give a rough estimate of the plasma velocity. Furthermore, when all parameters but one are held constant, this formula provides a basis for observing the effect of varying that parameter.

Figure 4, for example, presents the vane-deflection angles observed when the voltage applied across the drive coil was varied while the power to the RF coil was held constant and the pressure was maintained at 0.125 mm Hg. If it is assumed that the gas temperature is 300° Kelvin, the drag coefficient is 1, and the mass flow of mercury vapor is negligible compared with that of argon, then the plasma velocity corresponding to the deflection of $15^{\circ}30'$ obtained at an applied voltage of 440 volts is about 450 meters per second, according to the vane-deflection velocity formula. However, the use of this method for measuring supersonic velocities, and especially the assumption of a drag coefficient of 1, may be questioned. (The value of the drag coefficient for a flat plate normal to a stream in the low-supersonic velocity range is discussed briefly in ref. 10.)

Furthermore, with such an intense discharge (the plasma appears bright even when observed through heavy welders' goggles), the degree of ionization is significant. The vane deflection might then be interpreted as the combined effect of extremely fast charged particles together with a subsonic neutral gas flow.

The results obtained by the vane-deflection method indicated a notable difference between the performance of this induction accelerator and that of the d-c accelerator reported in reference 4. In that reference, it was observed that the d-c accelerator appeared to operate more efficiently as the pressure was raised from 1 to 10 mm Hg. Such an effect was not observed with the induction system, which performed well even at a pressure of 0.01 mm Hg. For example, at a pressure of 0.01 mm Hg the vane deflection was $9^{\circ}20'$, which corresponds to a velocity of about 1,250 meters per second (according to the vane-deflection formula), as compared with a velocity of about 450 meters per second obtained at a pressure of 0.1 mm Hg, and 225 meters per second at 1.0 mm Hg. This result may possibly be associated with the capacity of induced discharges to conduct large currents at very low pressures (ref. 11).

As previously noted, a pair of longitudinally displaced photocells should indicate the movement of light-intensity variations associated with the rise and decay of current on each half-cycle. Figure 5 is a sequence of oscillographs that demonstrates the effect of increasing the distance between the photocells while the pressure and input power are held constant. This sequence indicates clearly that the displacement between the traces increased as the photocell spacing was increased. There is a preliminary indication that this signal displacement is a relatively weak function of the pressure and power input over a restricted range of these parameters. It seems, therefore, uncertain whether the motion indicated by this signal displacement actually corresponds to the movement of charged particles; especially in view of the fact that the velocity of this motion always appears to be of the order of 10^4 meters per second, a value which appears rather high even for an ambipolar type of motion.

Qualitative Discussion of Accelerator Design and Operation

There are certain advantages in the use of a motor generator for driving an induced discharge, as for example, the relative economy of this type of power equipment. On the other hand, it is rather difficult to start and maintain an induced discharge at the frequency obtainable with such equipment. The relatively low frequency allows sufficient time for some deionization to occur as the current passes through zero. If the loss of ionization by diffusion and recombination during this period is excessive, the discharge will not be maintained. Furthermore, since the plasma is equivalent to a single-turn secondary, the induced potential gradient is proportional to the voltage per turn, which is relatively low for a primary coil operating in the audio-frequency range. Of course, so long as the ionization persists in the gas, a relatively low induced voltage should suffice to drive the current, inasmuch as there are no electrode potential drops in an induced discharge.

With the 10-kilocycle coil alone, an induced discharge could not be obtained in argon or in argon seeded with mercury vapor; and even when the discharge was started by a higher frequency auxiliary coil, it was not maintained by the 10-kilocycle coil when the high-frequency power was turned off. One reason for this difficulty, of course, is the ionization losses by diffusion, but there is another less obvious problem. It appears that if charged particles exist initially in the coil region, they are effectively swept away by the outward movement of the magnetic field as the current rises during the first half-cycle. The induced potential gradient due to the 10-kilocycle coil alone is then incapable of "breaking down" an induced discharge on the next half-cycle.

The charged particles are driven away from the coil because the current in the gaseous secondary is out of phase with that in the primary coil. The basic mechanism is similar to that utilized in the well-known laboratory experiment demonstrating the electromagnetic repulsion of a metal ring (see ref. 12, for example). Of course, with a plasma secondary the force is applied directly only to the charged particles and is conveyed to the neutral gas by collisions.

The radio-frequency coil insures that even though charged particles are periodically swept out of the discharge, there is always a highly conductive plasma ring to act as a secondary.

With the use of the auxiliary radio-frequency ionizing coil, the operation of the accelerator was exceptionally stable. With the present apparatus, running times were limited to periods of 20 seconds to 1 minute because the gradual temperature rise of the iron core had a detuning effect on the RF circuit. However, this time limitation can be easily overcome by water-cooling the core, as was done in the investigation reported in reference 11.

Seeding the argon with the room-temperature vapor pressure of mercury considerably facilitates the maintenance of the induced discharge. With this seeding, less radio-frequency power is required for stable performance, and the operation of the accelerator is less sensitive to the influence of gaseous impurities in the system and to the detuning effect of the heating of the iron core.

The iron wire core is used not only to facilitate tuning and coupling, but also to improve the shape of the magnetic-field distribution. Its use was suggested not only by reference 11, but also by reference 13, in which the proposal was made that the use of such a core might improve the performance of an apparatus for electromagnetically accelerating a shock wave. The coil tuning and the general effectiveness of the accelerator are rather sensitive to the position of the core in the duct.

For these initial experiments, the design of the accelerator ducting was dictated by considerations of simplicity in fabrication. It is believed that with some modification of this design, the induction accelerator will be effective when incorporated into a linear supersonic-flow system. Such a system may utilize an annular nozzle with the drive coil distributed along the exterior of the diverging part of the nozzle (see fig. 6).

CONCLUDING REMARKS

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A continuous-flow electrodeless plasma accelerator has been operated over a pressure range from 0.005 mm Hg to 25 mm Hg. Vane-deflection measurements indicate that the velocity of the plasma increased as the pressure was lowered.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., October 24, 1961.

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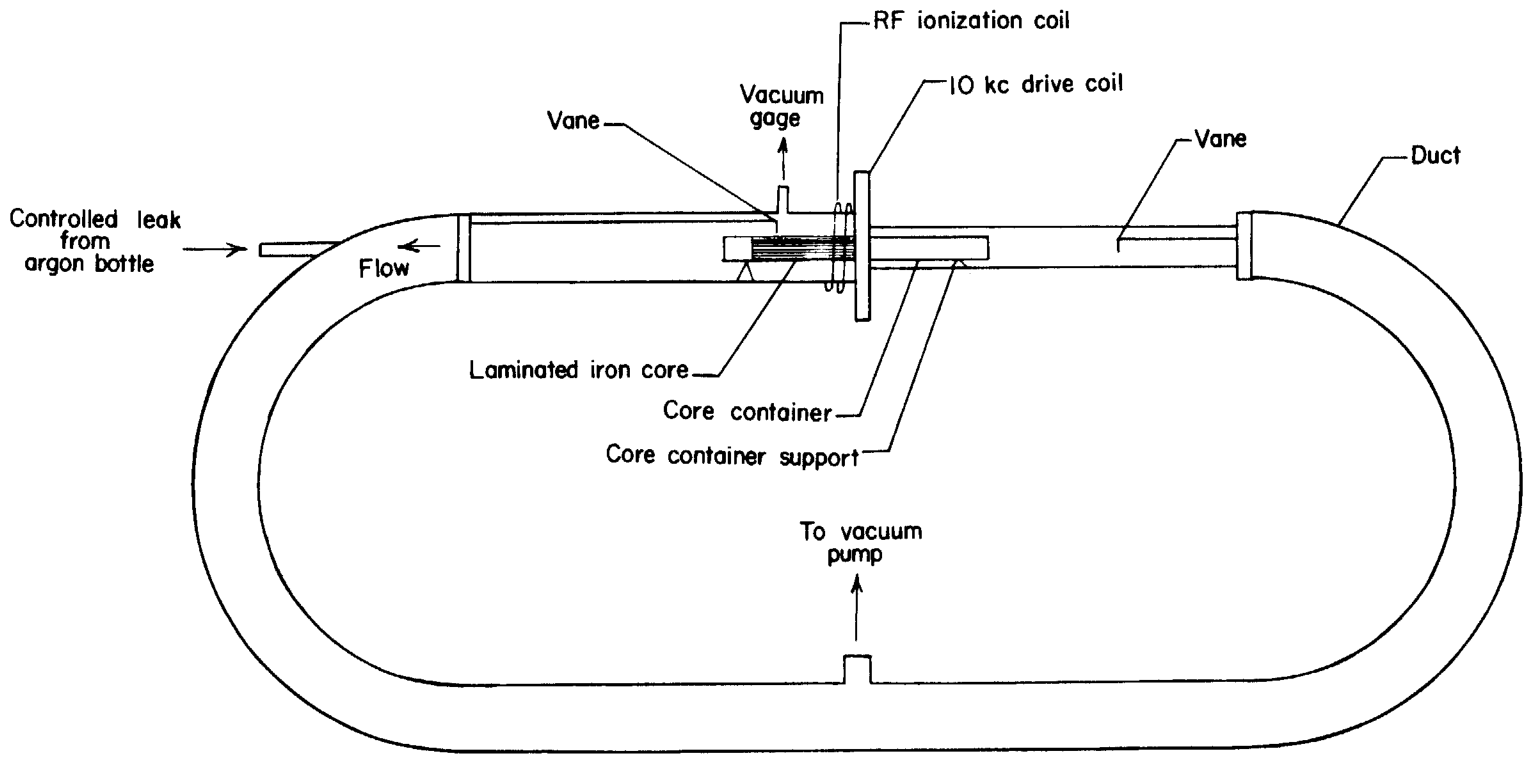

Figure 1.- Schematic diagram of alternating-current plasma-acceleration apparatus.

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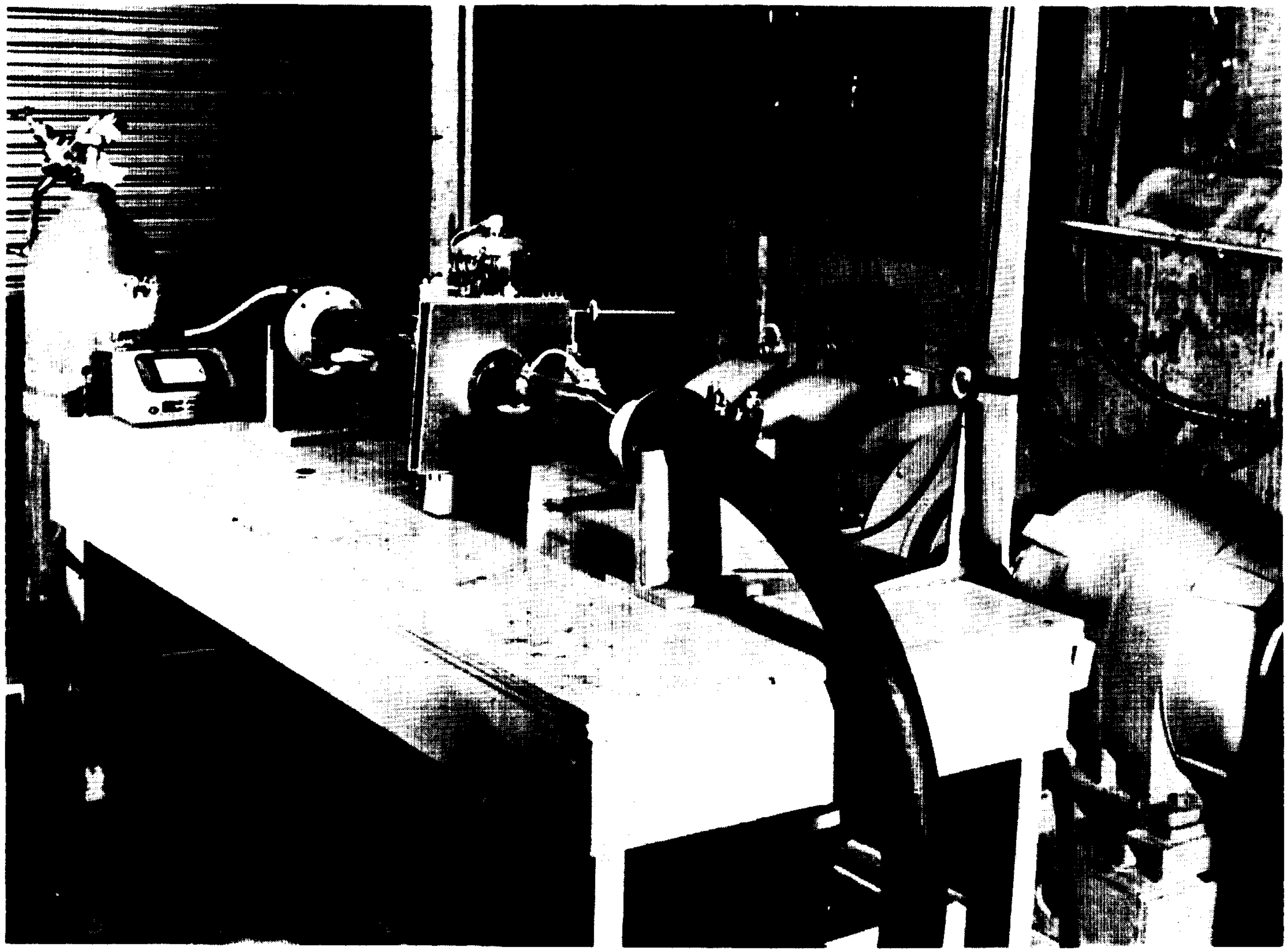

Figure 2.- Photograph of plasma-acceleration apparatus. L-61-6029

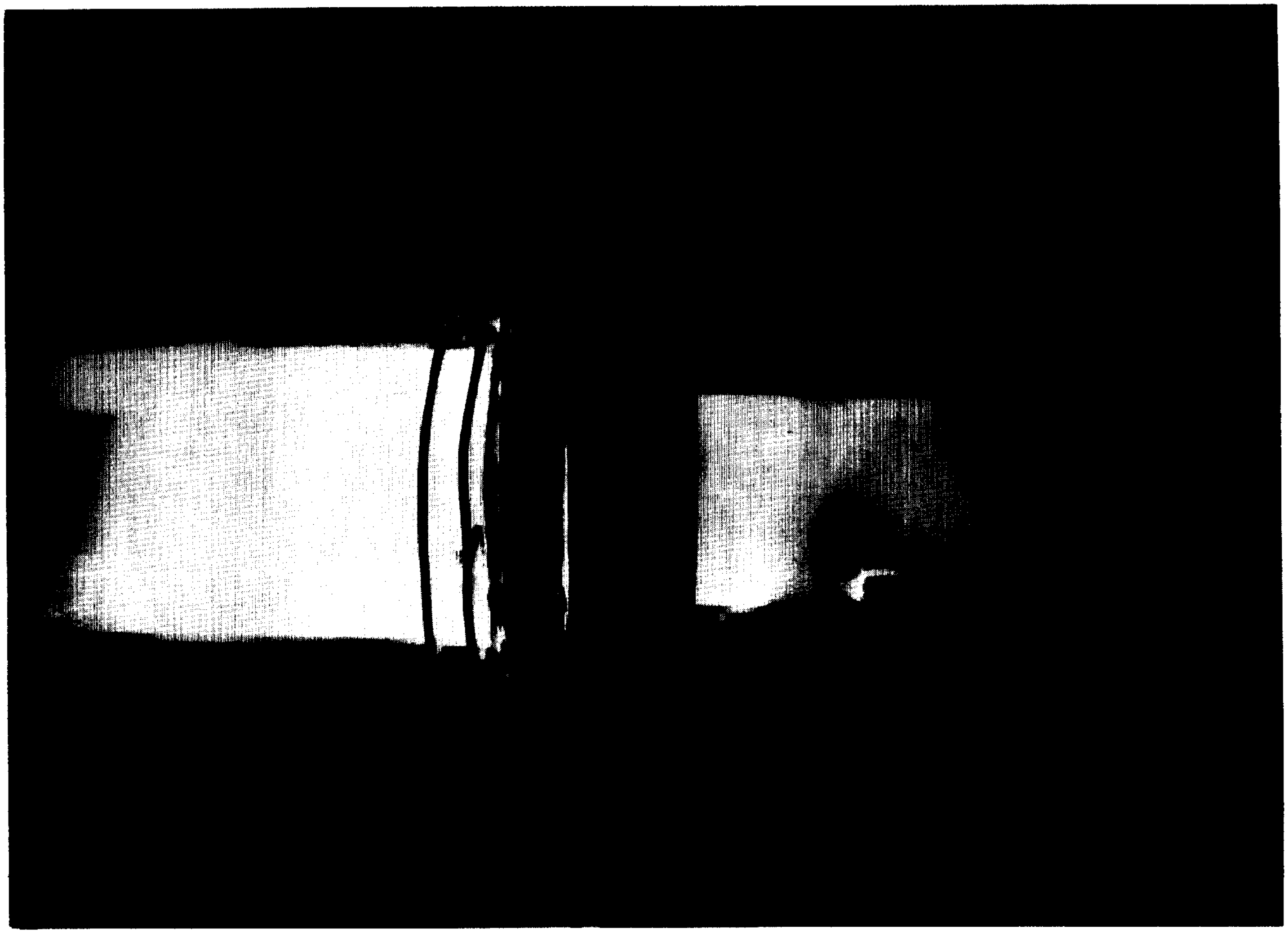

Figure 3.- Closeup of accelerator in operation. L-61-6031

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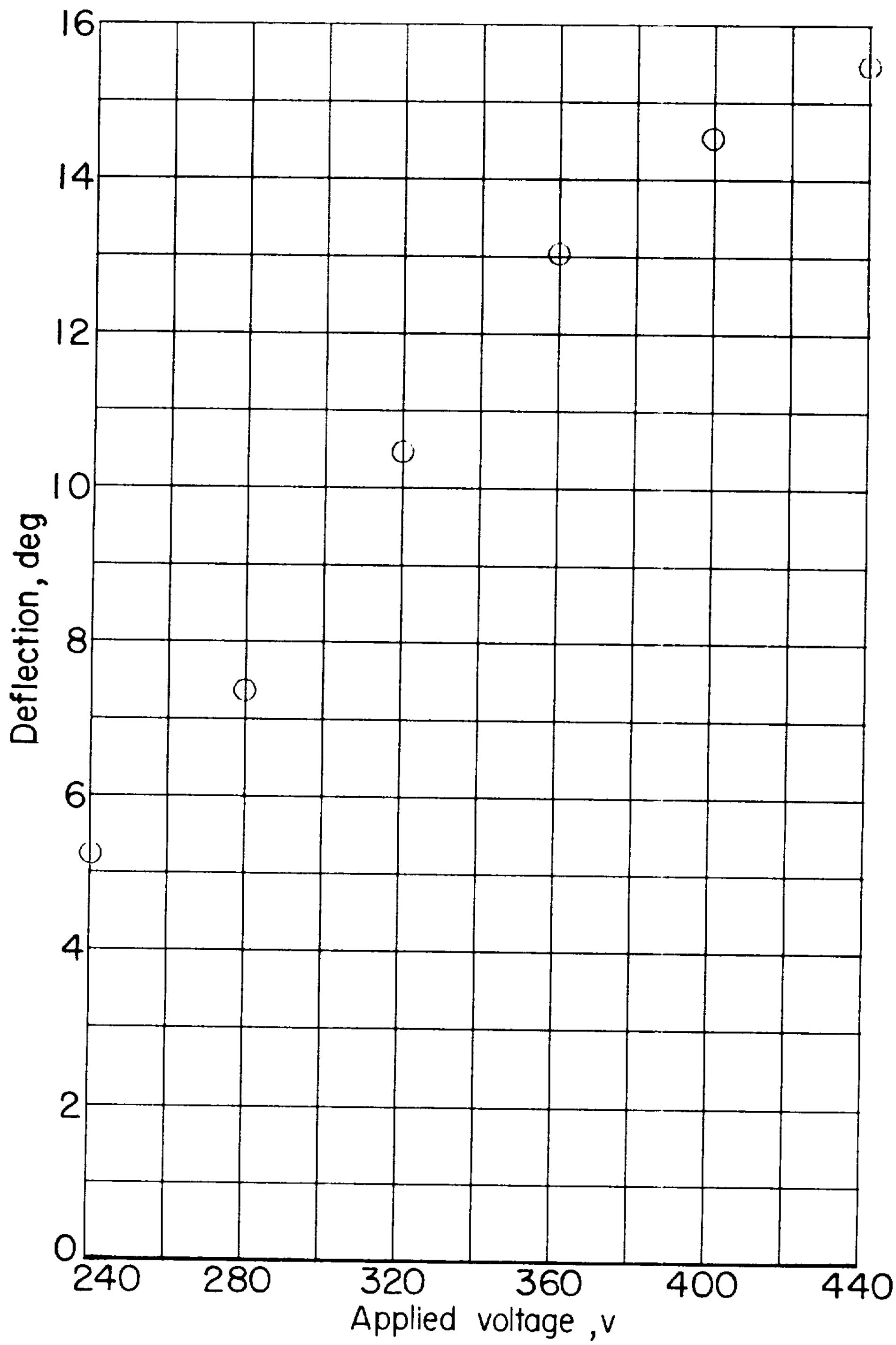

Figure 4.- Vane-deflection angle plotted against voltage applied across drive coil at a pressure of 0.125 mm Hg.

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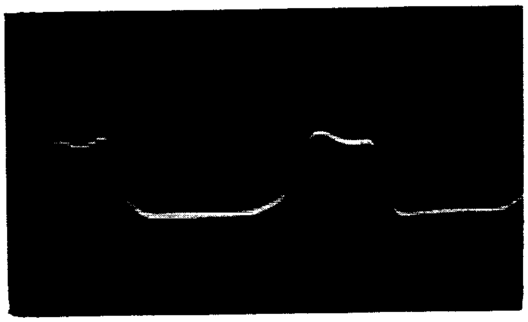
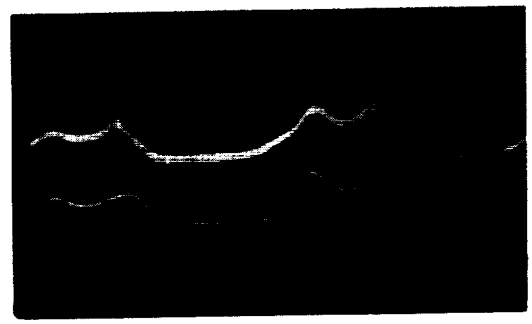
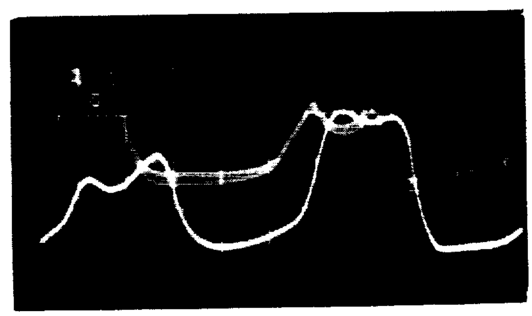


(a) Spacing: 0 centimeter.

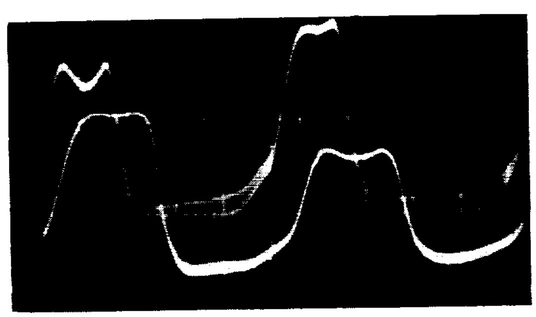


(b) Spacing: 2 centimeters.

(c) Spacing: 4 centimeters.



(d) Spacing: 6 centimeters.



(e) Spacing: 8 centimeters.

Figure 5.- Sequence of oscillographs demonstrating the effect of increasing photocell spacing. Oscilloscope sweep rate, 10^{-5} second per centimeter.

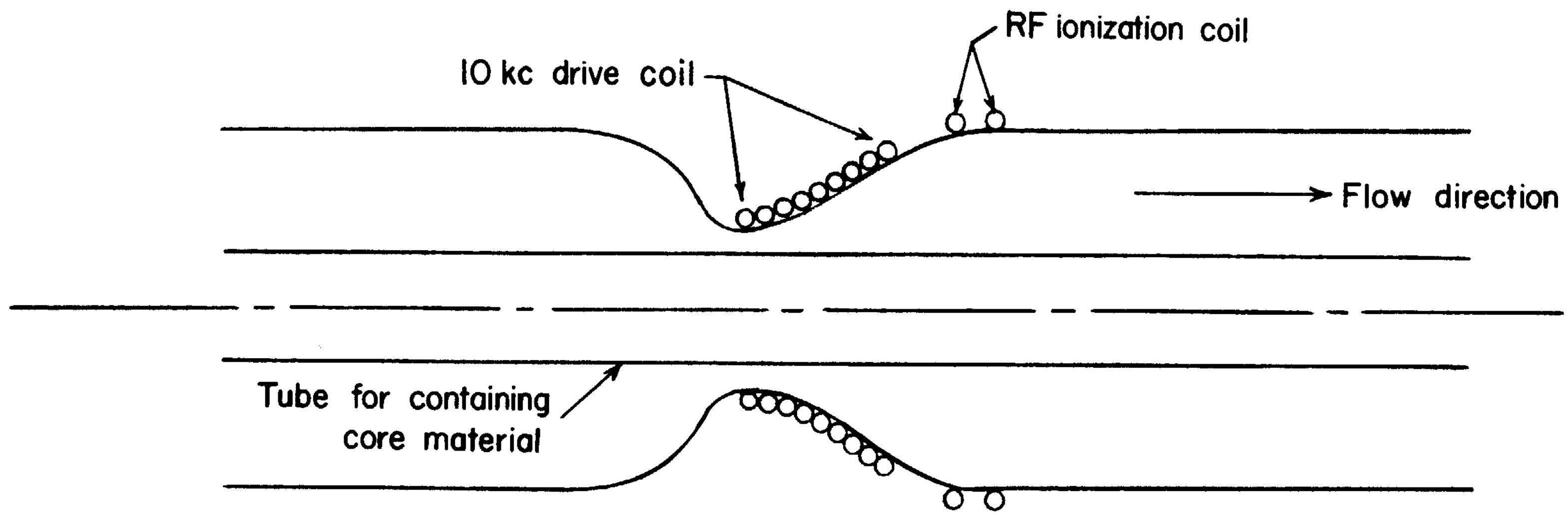


Figure 6.- Schematic design of a supersonic-flow system with induction accelerator.

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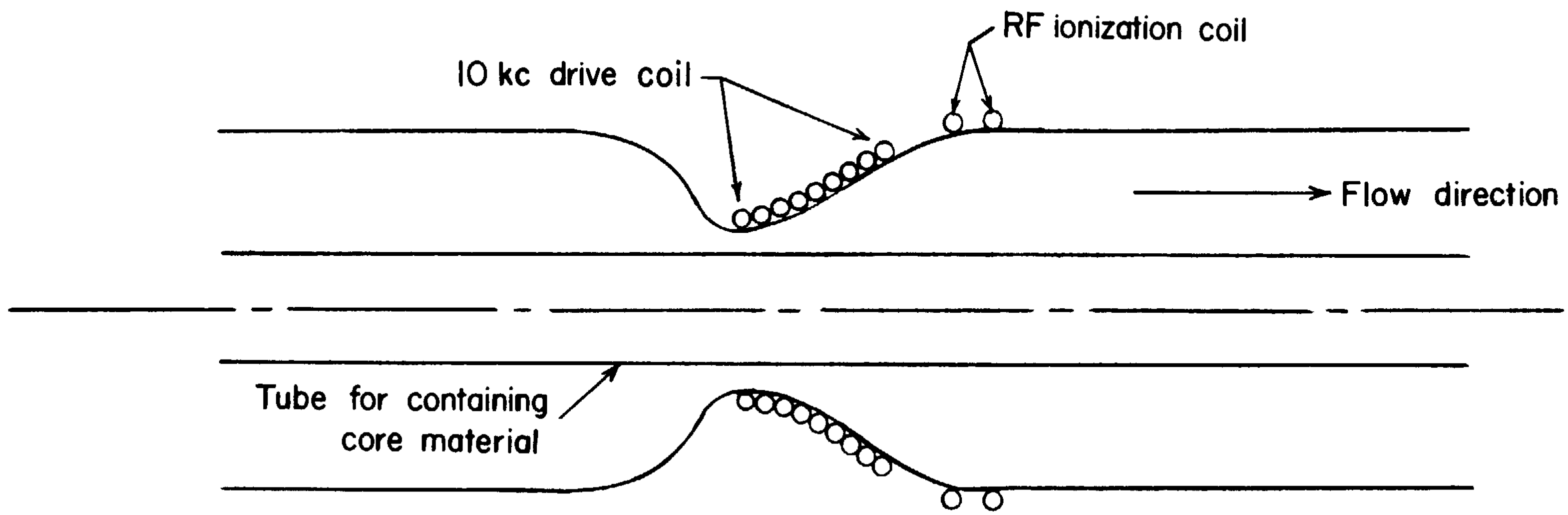

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